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The use of measured solar radiation to calculate the net radiation

by

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In calculations of the potential evapotranspiration from a crop surface during the summer half of the year, the net radiation is usually the most important term in the Penman formula. Actual measurements of net radiation are relatively few, but measurements of total solar radiation (direct plus diffuse) on a horizontal surface are being made at many more sites. In certain cases it is desirable to make estimates of the diurnal variation of net radiation - for example in experiments involving the evaporation of moisture from a cut or standing grass crop. A considerable number of papers have been published in the last ten years dealing with relationships between net and total solar radiation, and this memorandum represents an attempt to summarise some of the results obtained.

Definitions

R = net radiation

Q = incoming short wave radiation from sun and sky

S = direct radiation from the sun

D = diffuse short-wave radiation from the sky

L = net long-wave radiation (positive in a downward direction)

L_d = downward flux of long-wave radiation from the atmosphere

L_u = upward flux of long-wave radiation from the surface

α = albedo or reflection coefficient for short-wave radiation

σ = Stefan-Boltzmann constant = 5.67×10^{-9} mWcm^{-2}

T = temperature in ^{o}K

C = fraction of sky covered by cloud

n = hours of sunshine as measured by a Campbell-Stokes recorder

N = maximum possible hours of sunshine

All radiation values are expressed in mWcm^{-2}

The conversion factors to other commonly used units are:-

$$1 \text{ mWcm}^{-2} = 1.4333 \times 10^{-2} \text{ cal cm}^{-2} \text{ min}^{-1}$$
$$= 0.8600 \text{ cal cm}^{-2} \text{hr}^{-1}$$

By definition $R = (1-\alpha)Q + L$ ----------(1)

$= (1-\alpha)(S+s) + L_d - L_u$ --- (2)

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The reflection coefficient

For a green crop completely covering the ground and solar elevations greater than 30°, the reflection coefficient is generally about 0.25. For solar elevations of less than 30° the value of α increases to about 0.35 at 10° elevation (Davies and Buttimor 1969). However, the flux of incoming short-wave radiation is relatively low at such elevations and for the summer half of the year at latitudes corresponding to those of the British Isles a mean daily value of about 0.25 for a green crop can be used. For bare soil α may vary from about 0.05 to about 0.35 depending on soil type and degree of dryness (a summary of values which have been obtained is given in Linacre (1969).

Long-wave radiation

The net long-wave radiation is given by the difference between the downward flux of long-wave radiation from the atmosphere and the upward flux of long-wave radiation from the surface.

Assuming an emissivity of nearly one, the upward flux is given by $L_u = \sigma T_A^4$ mWcm^{-2} - - - - - - - -(3)

where T_A is the surface temperature in °K

In most cases the surface temperature is not measured, but the temperature T in a Stevenson screen is usually available. The difference in temperature $T_A - T$ depends on the time of day, the meteorological conditions and the nature of the surface. Under conditions of clear skies Monteith and Szeicz (1962) found that (measuring T_A from the upward flux of long-wave radiation) daytime values of $T_A - T$ could reach about 20°C for bare soil, 10°C for short grass, but only about ± 2°C for a fairly tall green crop which was well watered. At night all the surfaces were colder than the screen temperature by about 3°C for bare soil or a tall crop, and up to 6°C for short grass.

In the case of dry bare soil the radiative temperature of the surface rises rapidly during the day and the net radiation is correspondingly decreased. A similar effect could be expected to occur when a heavy grass crop has been cut and removed.

In many cases one is interested in estimating the net radiation to a fairly tall, well watered crop, and in this case the assumption $T_A = T$ will normally be adequate. If at 20°C $\Delta T = T_A - T = 2°K$ $\Delta L_u = 1.1$ mWcm^{-2} and $L_u = 41.8$ mWcm^{-2}.

The downward flux of long-wave radiation gives rise to a considerable number of problems. If the vertical distribution of temperature and humidity are known from radiosonde ascents it is possible to use radiation charts to calculate the downward flux. Alternatively empirical formulae which have been obtained relating the downward long-wave radiation to screen observations of temperature and perhaps humidity, may be used. In general these formulae are only really appropriate to periods of at least a day.

The Brunt type of formula for long-wave radiation from clear skies gives:-

$L_d = (0.53 + 0.065\sqrt{\bar{e}})\sigma T^4$ - - (4), where $\bar{e}$ is the mean vapour pressure at screen level in mb. In the presence of cloud it is assumed that the cloud radiates as a black body at the temperature of the cloud base.

/over

i.e. $L_d = (1-C)L'_d + C\,T_c^4$ - - - - - - - - - - (5)

where L'_d is the downward flux of long-wave radiation from clear skies and C is the fraction of sky covered by cloud. This formula ignores the absorption of long-wave radiation by water-vapour and carbon dioxide between the cloud and the surface.

The temperature of the cloud-base (T_c) relative to screen temperature T will vary considerably under different synoptic conditions. For instance cloud with a base at 800m (2600ft) might have a temperature about 6°C below screen temperature, while with thick frontal clould the cloud base temperature might be close to the screen temperature. In general unless data from radiosonde ascents are available, probably the best estimate would involve the use of the mean screen temperature, modified by a correction term. For periods of less than a day it would still seem to be advisable to ignore the diurnal variation in screen temperature, and use the mean daily value.

Another expression that has been calculated for the long-wave radiation from clear skies is that of Swinbank (1963) using data from a number of sites in different parts of the world. He obtained a regression of the form:-

$$L_d = -17.09 + 1.195\sigma T^4 \text{ mWcm}^{-2} \text{ - - - - - (6)}$$

This depends only on the screen temperature.

Taking T = 293°K and $\bar{e}$ = 14mb, the formulae give for clear skies:-

Brunt $L_d = (0.53+0.065\sqrt{\bar{e}})\,\sigma T^4 \text{ mWcm}^{-2} = 32.17 \text{ mWcm}^{-2}$ - - (7)

Swinbank $L_d = -17.09+1.195\sigma T^4 \text{ mWcm}^{-2} = 32.84 \text{ mWcm}^{-2}$ - - (8)

If $L_u = \sigma T^4 = 41.78 \text{ mWcm}^{-2}$, then the formulae give:-

Brunt $L = -9.6 \text{ mWcm}^{-2}$

Swinbank $L = -8.9 \text{ mWcm}^{-2}$

Swinbank (1963) asserted that the use of a regression involving only the screen temperature T fitted data from a variety of stations in the world better than did the Brunt relationship which also incorporated the vapour pressure. Observations were made at Kerang, 200 miles north of Melbourne, and in the Indian Ocean, as soon after dark as possible with a converted Funk net radiometer. Data from Benson, Pic du Midi, and Aspendale also fitted a regression of the form:- $L_d = a+b\sigma T^4$ with similar values of a and b. Where strong temperature gradients occur at screen level - for example with the formation of strong temperature inversions at night or lapse rates during the day - errors of the order of 3mWcm^{-2} in the case of inversions or 1.5mWcm^{-2} in the case of lapse rates are likely to arise. The diurnal variations of the downward long wave radiation are therefore exaggerated by the application of the regression involving the screen temperature throughout the period.

It would appear that for most purposes the Swinbank formula is generally sufficiently accurate in estimating the downward flux of long-wave radiation over periods of a day or longer and it is more easily calculated than the Brunt type of formula. Linacre has shown that, assuming that $T_A = T$, the net long-wave radiation can be approximated by the form:-

$L = -1.085 \times 10^{-1} (100-t) mWcm^{-2}$ - - - - - - - - (9) where t is the screen temperature in °C.

Using the cloudiness C, the Swinbank formula gives:-

$$L = (1-C)\left[-17.09+1.195\ \sigma T^4\right] + C\sigma T_c^4 - \sigma T_A^4 \text{ - - - - (10)}$$

If it is assumed that $T_c = T_A = T$ then this formula can be written as:-

$$L = (1-C)\left[0.195\sigma T^4 - 17.09\right] mWcm^{-2} \text{ - - (11)}$$

Frequently the cloudiness term (1-c) is replaced by an expression involving the ratio of the measured hours of sunshine n to the total possible hours. This has the form:-

$$f = \left[a + (1-a)\frac{n}{N}\right] \text{ - - - -(12)}$$ Various values have been suggested for the constant a in the range $0.10 \leq a \leq 0.30$. Linacre (1968) uses a = 0.20, while the value used in the M.A.F.F. bulletin "Potential Transpiration" is 0.17. The use of such an expression has the effect of applying a correction to the cloud base temperature T_c as compared with the screen temperature T.

For cloudy skies $\left(\frac{n}{N} = 0\right)$ the use of

$$L = (0.17 + 0.83\frac{n}{N})(0.195\sigma T^4 - 17.09) mWcm^{-2} \text{ - - (13)}$$

gives $L = -0.17 \times 8.94 mWcm^{-2} = -1.52 mWcm^{-2}$

using equation (10) with C=1

if $L = \sigma T_c^4 - \sigma T_A^4 = -1.52 mWcm^{-2}$

then $T_c = 290°K$ and $T - T_c \simeq 3°C$ if $T = 293°K$

i.e. the use of this expression for f implies a mean cloud base temperature that is about 3°C below the screen temperature.

Monteith (1961) using Kew data found that over a year the mean difference between calculated and observed values of L could be accounted for by a mean difference between cloud base and screen temperature of -1.7°C If a complete cloud cover is present, the measured value of L is normally close to zero, and the use of "f" may overestimate net long-wave radiation loss. Underestimation may occur if high clouds are present.

The diurnal variation of the incoming long-wave radiation with clear skies appears to vary considerably at different geographical locations and on different days. Monteith and Szeicz (1961) at Rothamsted, England found that the diurnal variation of the outgoing long-wave radiation was considerably greater than that of the incoming component, but Stanhill, Hofstede and Kalma (1966) in Israel and Idso, Baker and Blad (1969) at St. Paul, Minnesota, U.S.A., observed that on several occasions the incoming long-wave radiation increased more during the day than did the outgoing long-wave radiation. More information is required on the form of the diurnal variation of the net long-wave radiation over the British Isles before an appropriate value can be used in calculations of net radiation for periods of less than a day. During clear conditions in summer the net long-wave radiation has typically a night-time value of about $-8 mWcm^{-2}$ with a diurnal range of about $12 mWcm^{-2}$. Under the same conditions the diurnal range in the net short-wave radiation $(1-\alpha)Q$, is about $60 mWcm^{-2}$ and in the absence of further information on changes in L, it would appear to be better to use a mean daily value for the net long-wave radiation.

A major difficulty in calculating the net long-wave radiation for short periods is likely to lie in the estimation of the cloudiness factors C or f. With a complete cover of cloud Q may be reduced to about 10% of its clear sky value while L will change to a value close to zero as compared with a clear sky value of about $-8 mWcm^{-2}$. It may be possible to deduce the cloudiness from sunshine records, observations of cloud cover - including use of an automatic cloud-base recorder - or perhaps from the recorded solar radiation as a fraction of maximum radiation possible for that period.

For periods of a day Linacre (1969), using data from Chaka's Kraal (South Africa), and the simplified form of the equation for net radiation i.e.

$$R = (1-\alpha)Q - 2{\cdot}17\times10^{-2}(1+4\tfrac{n}{N})(100-t)\ mWcm^{-2}.$$

obtained a standard error of about $1.4 mWcm^{-2}$ for the estimation of net radiation from solar radiation, screen temperature and hours of sunshine. This amounted to a random error of about 12% of the net radiation. For weekly values the random error was reduced to about 6%. Almost as accurate estimates could be obtained using a relationship between t and Q to derive t.

Although random errors in estimating the net radiation were relatively small, the results from Chaha's Kraal together with those from other stations, including Kew, showed a general underestimation of R of the order of $-1.4 mWcm^{-2}$. To correct for this Linacre suggested the use of an effective albedo of 0.20.

Another approach to the calculation of net radiation from solar radiation simply makes use of linear regressions which have been obtained between these two parameters at different locations. Such regressions generally vary from place to place depending on the climatic conditions at the different sites, and particularly on the mean cloudiness. If only clear sky situations are considered, however, similar regressions are obtained at widely varying sites.

The form of the regression equation may be expressed as

$$R = a(S+D)+b \quad \text{- - - - - - - - - - - - - - - (15)}$$

of $$R = a'(1-\alpha)(S+D)+b' \quad \text{- - - - - - - - - -(16)}$$

The second equation gives the regression of the net long-wave radiation on the net short-wave radiation.

The regressions are normally expressed either as the relationship between hourly values of net radiation and solar radiation, or between daily totals of net radiation for daylight hours and the daily total of solar radiation. If only daily totals are available to calculate the regression, there are likely to be insufficient points close to the origin to give realistic values for the constants in the regression equation. Idso, Baker and Blad (1969) have discussed the problems of obtaining regressions for daily totals and shown that in such cases it is necessary to use the regressions for hourly values of net on solar radiation to obtain a reliable relationship. The slope of the regression should be the same for both hourly totals and daily totals. Over a bare soil surface the relationship between net and solar radiation for hourly totals shows a much more marked diurnal variation than over a fairly tall freely transpiring crop. This is due to the very considerable increase in temperature of the soil surface during the day.

Pooling data from the results obtained from different crops Fritschen (1967) estimated that for daily totals, the standard error in estimating the net radiation from the solar radiation using a pooled regression equation was about 35cal.cm^{-2} (or 39mWhrcm^{-2}), which for sunny days would be about 10% of the net radiation. This is only appropriate generally for the condition of clear skies. He found that the use of net short-wave radiation $(1 - \alpha)(S+D)$ in the regression did not improve the relationship between net and solar radiation.

Regressions which have been quoted for clear skies include,

$R = 0.93(1-\alpha)Q-0.12$ cal cm^{-2} min^{-1} - - - - - -(17)

$\equiv 0.93(1-\alpha)Q-8.4$mWcm^{-2}

$= 0.697Q-8.4$mWcm^{-2} - - - - - - - - - - - - - -(18) if $\alpha = 0.25$

Monteith and Szeicz (1962) at Rothamsted, England.

$R = 0.789Q-11.25$ cal cm^{-2} hr^{-1} - - - - - - - -(19)

$\equiv 0.789Q-13.1$mWcm^{-2} - - - - - - - - - - - - -(20)

Idso, Baker and Blad (1969) at St. Paul, Minnesota.

$R = 1.06(1-\alpha)Q-0.14$ cal cm^{-2} min^{-1} - - - - - -(21)

$\equiv 1.06(1-\alpha)Q-9.8$mWcm^{-2}

$= 0.795Q-9.8$mWcm^{-2} - - - - - - - - - - - - - -(22) if $\alpha = 0.25$

Stanhill, Hofstede and Kalma (1966) in Israel

$R = 0.734Q-0.12$ cal cm^{-2} min^{-1} - - - - - - - - (23)

$\equiv 0.734Q-8.4$mWcm^{-2} - - - - - - - - - - - - - -(24)

Fritschen (1967) in Arizona

Davies and Buttimor (1969) obtained regressions between net and solar radiation for conditions of variable cloud at Simcoe, Southern Ontario, Canada. Using results for all the crops the relationship obtained was:-

$R = 0.556Q-0.05$ cal cm^{-2} min^{-1}

$\equiv 0.556Q-3.5$mWcm^{-2}

Such a relationship is unlikely to fit the results for stations with different climatic conditions.

This type of approach to the problem of calculating the net radiation may be useful for totals for a day or longer where relationships have been obtained under the same climatic conditions between the net radiation and the solar radiation. Under conditions of variable cloud the accuracy obtainable will be considerably less than under clear skies. For periods of less than a day it is unlikely that this type of relationship can be used except under clear sky conditions.

Linacre (1968) considers that a better estimate of the net radiation can be obtained by the use of the more fundamental theory contained in the first part of this memorandum. This takes into account the observed cloudiness and temperature at a given site. However, more information is needed on the apparent underestimation of the net radiation which Linacre (1969) found in the application of this theory.

The Grassland Research Institute.
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